

Research in Inertial Fusion Sciences: Now and in the Future

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RESEARCH IN INERTIAL FUSION SCIENCES: NOW AND IN THE FUTURE*

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ABSTRACT

We review the current and future state of research in inertial fusion sciences. We describe the National Ignition Facility (NIF), the IFE development plan, applications of inertial confinement fusion (ICF) to various high-energy sciences, uses of petawatt laser systems, and concepts for the ICF integrated research experiment (IRE) and IFE power plants.

1. INTRODUCTION

Over the past several decades, significant and steady progress has been made in the development of fusion energy and its associated technology and in the understanding of the physics of high-temperature plasmas. While the demonstration of net fusion energy (fusion energy production exceeding that required to heat and confine the plasma) remains a task for the next millennium and while challenges remain, this progress has significantly increased confidence that the ultimate goal of societally acceptable central power production can be achieved (e.g., in cost, safety, and environmental considerations including waste disposal).

This progress has been shared by the two principal approaches to controlled thermonuclear fusion—magnetic confinement (MFE) and inertial confinement (ICF). ICF, the focus of this article, is complementary and symbiotic to MFE. As shown in Figure 1, ICF invokes spherical implosion of the fuel to achieve high densities, pressures, and temperatures, inertially confining the plasma for times sufficiently long ($t \sim 10^{-10}$ s) that ~30% of the fuel undergoes thermonuclear fusion.

The unequivocal demonstration of the physics of ICF including fusion energy gain is planned for the National Ignition Facility (NIF) and Laser Megajoule (LMJ) now under construction in the United States and France respectively within a decade.

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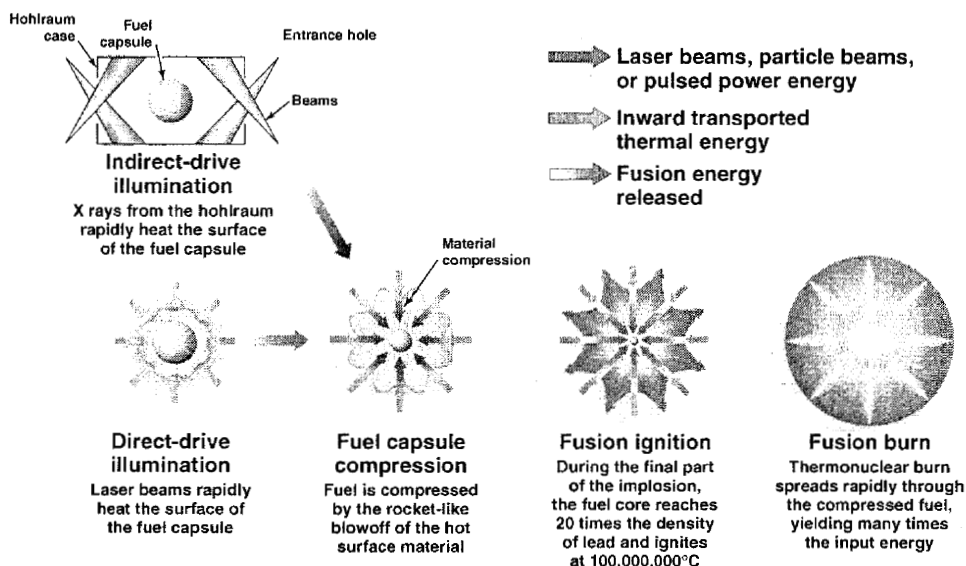


Figure 1. Four steps of the inertial confinement fusion (ICF) process.

In addition to fusion research, lasers and pulsed power facilities developed for ICF have proven to be outstanding research tools for the study of high energy density science. Lasers and pulsed power reproducibly concentrate energy in space and time and thus can create diagnosable plasmas that exist for picoseconds to tenths of microseconds at extremely high energy density. Such experiments can reach plasma electron and ion temperatures greater than 10^8 K, pressures greater than 10^{11} atmospheres, and radiation temperatures greater than 3.5×10^6 K. For example, using cylindrical gold hohlraums with diameters of 1, 1.6, and 4.8 mm on the Nova laser, radiation temperatures of 288 eV, 151 eV, and 94 eV have been created for times from 1 to 15 ns.¹ The resulting radiation fluxes of greater than 10^5 GW/sr/cm² can be used for fusion capsule compression or for a variety of measurements of basic material properties and/or physical processes. Large laser facilities doing such experiments include Nova, Omega, and Nike in the United States, Gekko XII in Japan, Phebus in France, Helen and Vulcan in the United Kingdom, and Iskra in Russia. Many other countries have smaller facilities but nevertheless are able to do outstanding science on them because even small lasers can achieve extreme conditions that are repeatable and diagnosable.

Furthermore, recent advances in sub-picosecond laser technology have opened new opportunities for the production of matter at ultra high specific energies ($\epsilon > 10^{10}$ joules/gram). Such high brightness lasers can now routinely achieve irradiances $> 10^{20}$ W/cm² and make possible, for example, the study of relativistic plasmas.²

In this article we will briefly describe the features and development plan for inertial fusion (Section 2) and the National Ignition Facility and its role in fusion energy development (Section 3). Section 4 will highlight some of the science that is derived from

ICF research in the fields of astrophysics, shock and condensed-matter as well as nuclear physics. Section 5 provides a short summary which hopefully communicates the excitement and challenge for the field over the next decade.

2. INERTIAL FUSION AND IFE DEVELOPMENT PLAN

As shown in Figure 1 and briefly described above, ICF relies on the inertia of the fuel mass to provide confinement sufficiently long that a significant fraction of the fuel (~20–30%) undergoes thermonuclear fusion. A spherical fusion capsule consists of an outer region, the ablator (consisting of doped plastic, polyamide, or beryllium), and an inner cryogenic shell of frozen equimolar deuterium-tritium. A laser, ion beam, or pulsed power driver, which can concentrate energy in space and time, generates a flux exceeding 10^{15} W/cm² which rapidly heats and vaporizes the ablator. The ablator rapidly expands outward and imparts radial inward momentum to the remaining shell. This spherical, ablation-driven rocket reaches implosion velocities in excess of 3×10^7 cm/s. The energy that can be delivered to the fuel is the product of the ablation pressure (a product of the areal mass ablation rate and exhaust velocity), typically 100 Mbar, and the volume enclosed by the shell (ignoring the volume of the final compressed state).

The implosion amplifies the ablation pressure a thousand-fold and in its final configuration, the fuel is nearly isobaric at pressures up to ~200 Gbar but consists of two effectively distinct regions—a central hot spot containing ~2 to 10% of the fuel and a dense, but cold Fermi degenerate main fuel region comprising the remaining mass. Fusion initiates in this central region where the hydrodynamic work and alpha particle deposition exceed conduction and radiation losses, and a thermonuclear burn front propagates radially outward into the main fuel, producing high gain ($G > 50$). The efficient assembly of the fuel into this configuration places stringent requirements on the details of the driver coupling, including the time history of the irradiance and the hydrodynamics of the implosion.

Figure 1 also shows the two principal approaches to ICF: indirect drive, where the driver energy is first converted into x rays in a high atomic number hohlraum that encloses the capsule with a characteristic Planckian temperature of 250–300 eV; direct drive, where the capsule is directly illuminated by the driver. Significant progress has been made in these two approaches, and today they both appear viable for achieving high gain.

With such targets producing high gain, an IFE power plant as shown in Figure 2 will consist of four components: (1) a driver which must efficiently ($\eta > 5\%$) and economically (cost <\$1.5B) produce the concentrated power (>500 TW) and energy (>~2 MJ) to drive a fusion implosion 5 times or more a second ($\langle P \rangle_{\text{Driver}} > 10$ MW); (2) a target factory that economically (~\$0.3/target) produces $\sim 3 \times 10^8$ high gain targets a year; (3) a target chamber that enables the successful injection of the IFE targets and the propagation of the driver energy, containing the fusion explosion ($E_{\text{fusion}} > 200$ MJ) and breeding tritium—all in an environmentally acceptable and cost-effective manner, and (4) a balance of plant that must efficiently (>40–50%) convert the high-grade fusion energy into electricity for the power grid.³

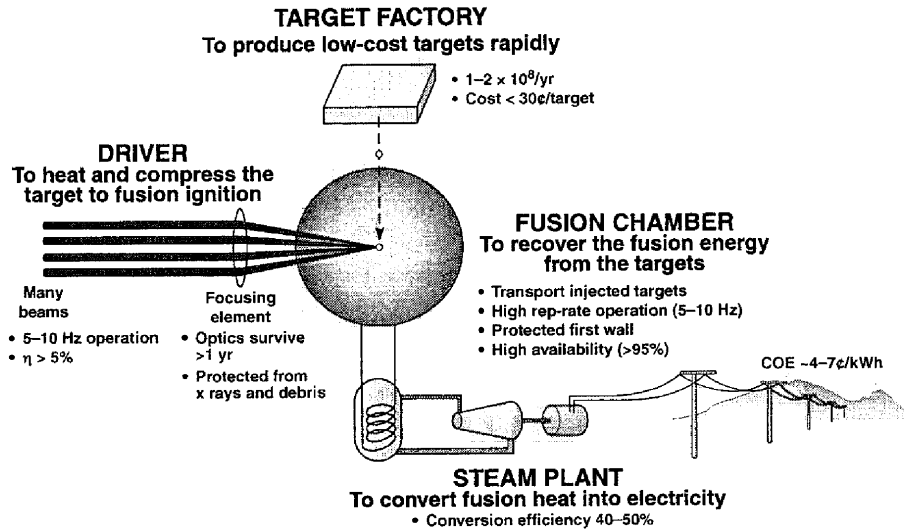


Figure 2. Inertial fusion energy (IFE) power plants will consist of four parts.

To produce affordable electricity from IFE presents many challenges. The cost of electricity (COE) must be in the range of 4-7¢/kW-hr and plant operation must be environmentally acceptable (i.e., plant components must allow for shallow burial and no off-site evacuation in a worst case accident). Target energy gains of 30 to more than 100 (depending on the driver efficiency) are required to keep the recirculating power low^{3,4}. From Figures 1 and 2, IFE also has many attractive features that include: (1) separability of the plant components allowing for parallel development and "local" optimization; (2) a high degree of modularity in components (for example, the driver would consist of hundreds to thousands of identical beamlines) allowing for cost-effective development, full-scale engineering and scientific prototypes, and economy of scale in manufacturing; (3) multiple, credible options in targets (direct and indirect), drivers (lasers, ions, possibly pulsed power), and chambers (ranging from neutronically thick liquids to dry walls facing the fusion explosion).

Another extremely important feature for IFE development is that, as discussed in the next section, it leverages the extensive target physics program supported by DOE for national security purposes, the accelerator development supported by the high-energy physics community, and the development of lasers for industry.

Given the progress in the field and the attractive features of IFE, a development plan has been formulated by the community that, if funded and successful, would lay the technical foundation for beginning construction of an Engineering Test Facility (ETF) in the second decade of the next century. The goal of this facility would be to produce average fusion power (in the range of 100 to 400 MW) and demonstrate the operability, environmental and safety features, and the economics of IFE for a project cost in the range of \$2B to \$3B.

The entire fusion community has formulated the IFE development program into a “road map” that is shown in Figure 3. This IFE-specific version shows the different stages of development and demonstration: concept exploration, proof of principle, performance extension, and fusion energy development (the ETF) leading to a demonstration plant. To progress to higher, more costly stages, specific scientific and technical objectives must be met. The existing ICF program engages the road map at the first three levels with significant ongoing investment by DOE’s national security program (illustrated by the shaded region in the performance extension). Examples of activities in the first level include exploring ways of extending the successful Z pinch efforts into an IFE concept (rep-rate, stand-off, waste stream), examination of the high-gain ($G > 200$) “fast ignitor” concept where isochroically compressed fuel is ignited by a separate high-intensity driver, and the exploration of high-gain ($G > 100$) indirect drive with lasers. Examples of the second stage include the development of high rep rate (> 5 Hz) 100 joule-class KrF and diode-pumped solid-state lasers (i.e., the Electra project at the Naval Research Laboratory, and the Mercury project at LLNL). Mercury and its goals are shown in Figure 4.

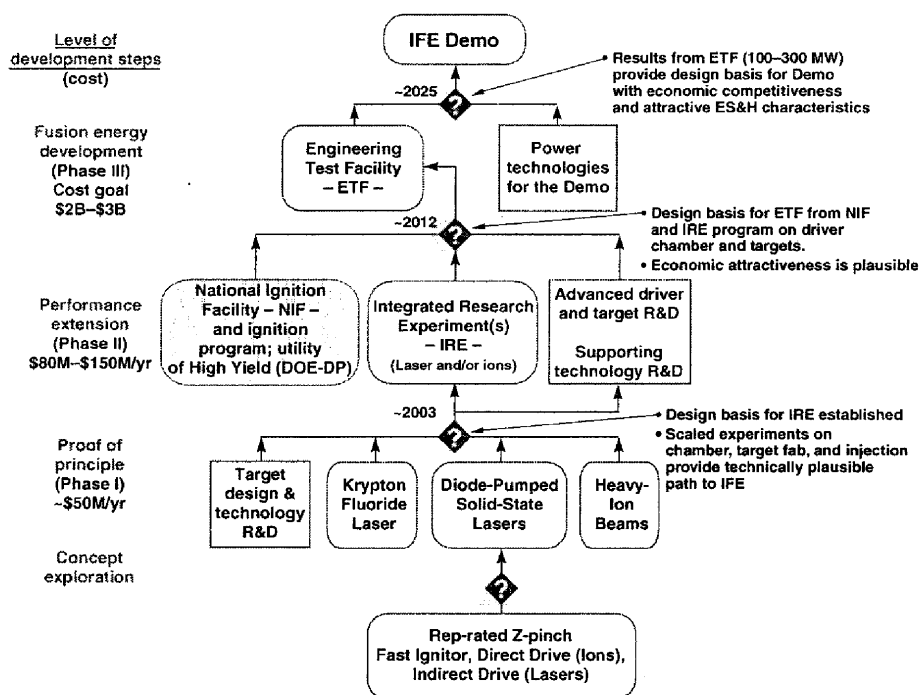


Figure 3. The Inertial Fusion Development Strategy is integrated with the Fusion Energy Road Map.

The third level includes the demonstration of ignition and gain on the single-shot National Ignition Facility (NIF) and the construction of high rep rate, multi-kilojoule (~15 kJ to 300 kJ) drivers that also address key chamber issues (driver chamber interface, beam propagation in the chamber, etc.). Because of such system objectives, these facilities have

been named integrated research experiments (IREs), and a heavy-ion example, along with its objectives, is displayed in Figure 5.

The results of the IREs and the target physics from the NIF, described in the next section, would form the basis for proceeding with an ETF.

3. THE NATIONAL IGNITION FACILITY (NIF)

Demonstration of the critical features of IFE targets (ignition and propagating thermonuclear burn) is a principal goal of the NIF, now under construction at Lawrence Livermore National Laboratory (LLNL).⁵ Figure 6 shows a schematic of the 192-beam, flashlamp-pumped, Nd: glass laser facility, whose output is frequency up-converted to an on-target wavelength of $0.35\ \mu\text{m}$. Table 1 lists the nominal output specifications of the NIF, and Figure 7 shows the state of construction as of June 1999, including the 10-meter-diameter target chamber. The NIF is scheduled for completion in late 2003, with ignition and gain experiments beginning in 2006–2007. As shown in Figure 8, the NIF is an extremely flexible facility with the ability to irradiate both indirect- and direct-drive targets with a variety of pulse formats including the complicated pulses required for high-gain ICF.

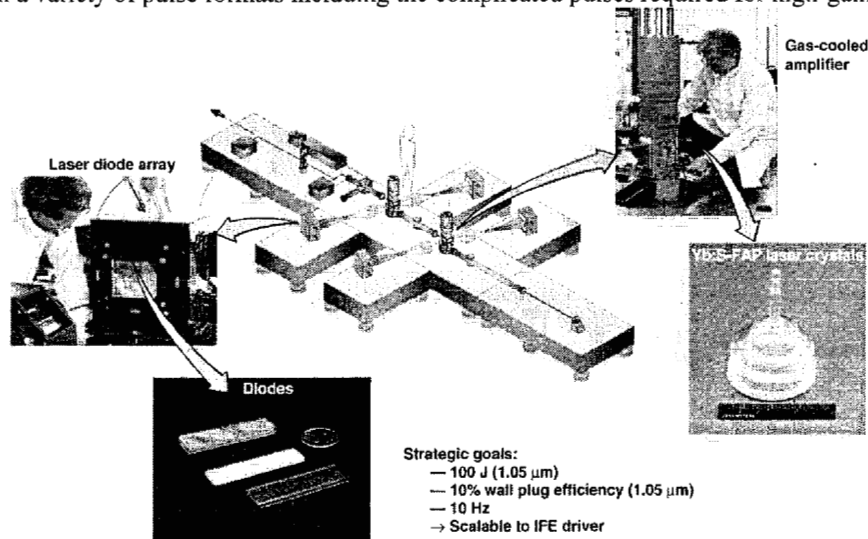


Figure 4. The Mercury laser: An example of an IFE-related laser activity over the next several years.

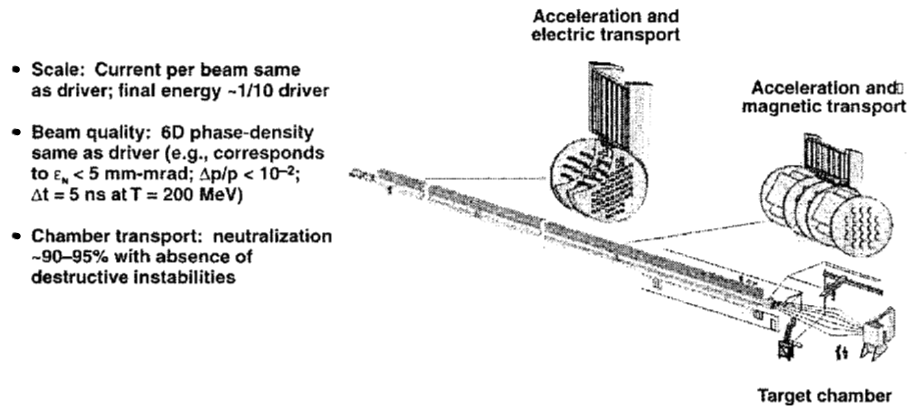


Figure 5. Heavy-ion Integrated Research Experiments (IREs) will play a major role demonstrating the feasibility of IFE: example, heavy ions.

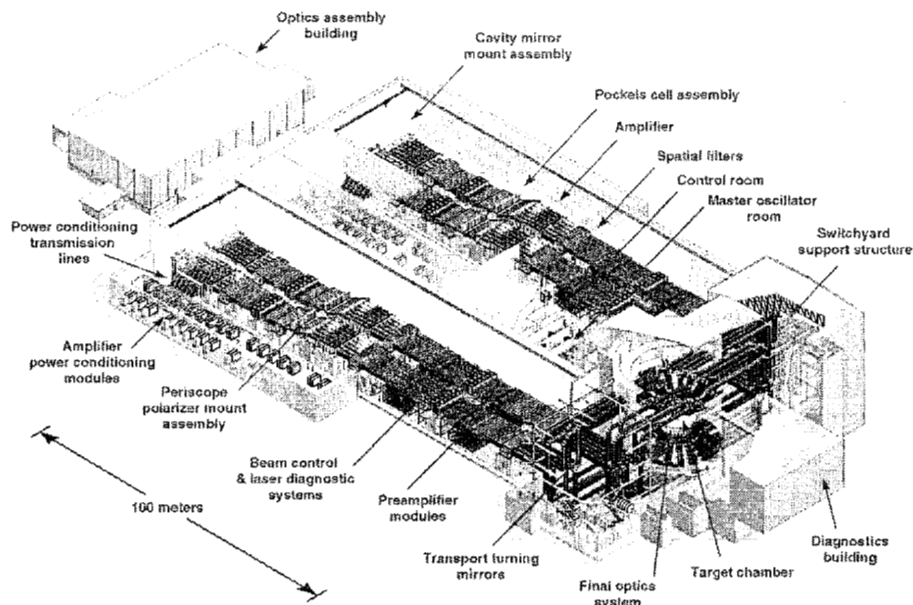


Figure 6. The National Ignition Facility and the LMJ will provide a unique opportunity for demonstrating critical elements of ICF target physics required for IFE.

Table 1. NIF top-level performance requirements.

Laser pulse energy (on target)	1.8–2.5 MJ (pulse shape dependent)
X-ray backlighting	Beams independently timed and located
Laser pulse shaping	Flexible (0.1 – >20 nsec in complicated pulse shapes)
Laser pulse peak power	>500 TW
Laser pulse wavelength	0.35 μm
Beam power balance	<8% rms over 2 ns
Beam pointing accuracy	<50 μm
ICF target compatibility	Cryogenic and noncryogenic
Annual fusion yield compatibility (indirect and direct drive)	50 shots with yield 20 MJ 1200 MJ/y annual yield
Maximum DT fusion yield/shot	(~100 MJ)
Experiments/year *	>700

* Program is now under way with UK collaboration to increase the shot rate to >1000.

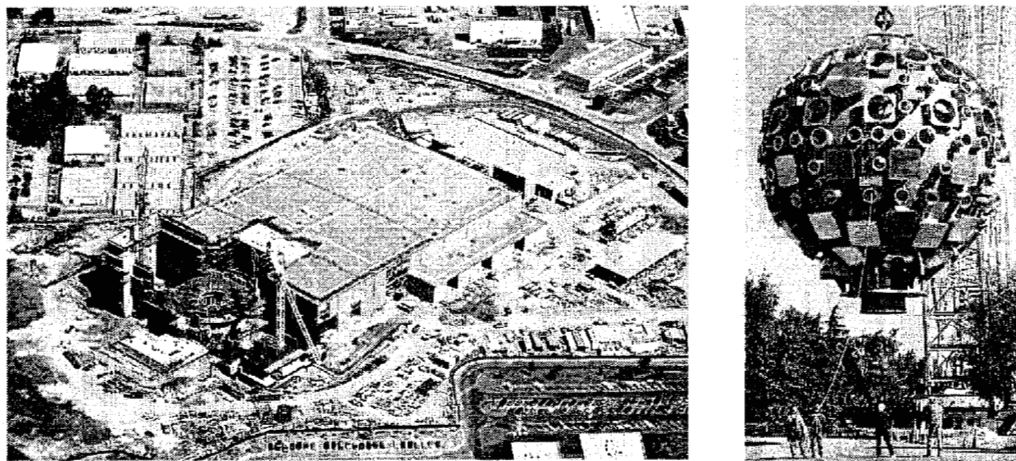


Figure 7. Aerial view of the NIF looking north (April 23, 1999); moving target chamber (June 6, 1999).

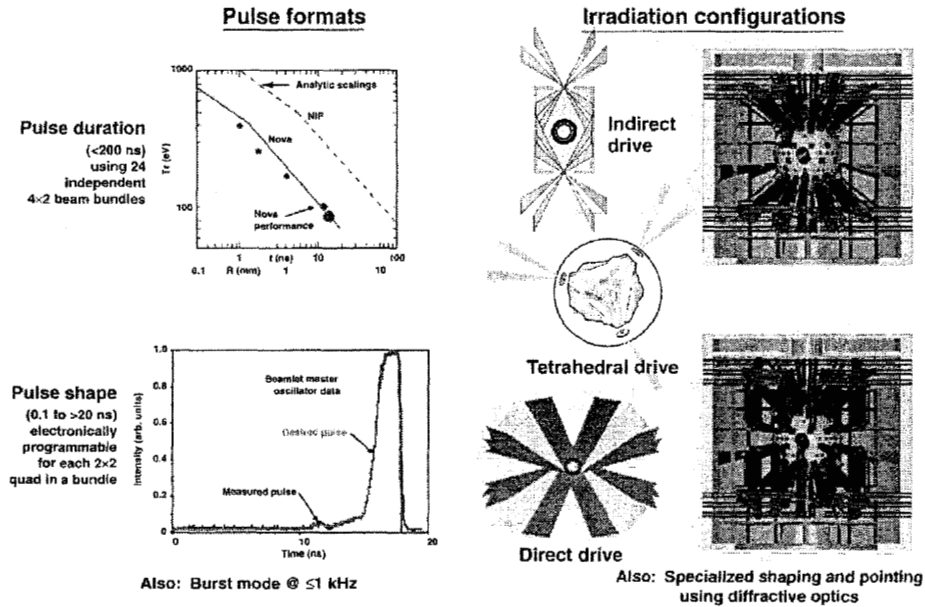


Figure 8. The NIF will be a flexible, versatile facility.

As mentioned in the previous paragraph, the principal goal of the NIF is to demonstrate ignition and modest gain. Figure 9 shows the gain curves calculated over the range of operating conditions for the NIF. The physics of indirect and direct drive is well established whereas the predicted impressive gains for the fast ignitor are based on models that have not yet been validated by experiment. The baseline indirect- and direct-drive targets, which have nominal gains of 10 and 30, are shown in Figure 10 (which also illustrates the pulse format flexibility of the NIF). Numerous target designs, with absorbed energies greater than 900 kilojoules, calculate to ignite and burn.

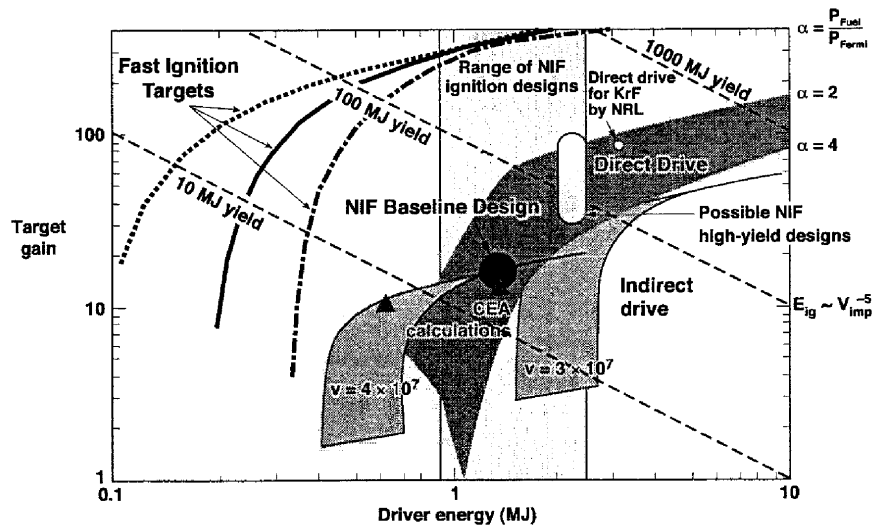


Figure 9. The NIF will map out ignition and gain curves for multiple target concepts.

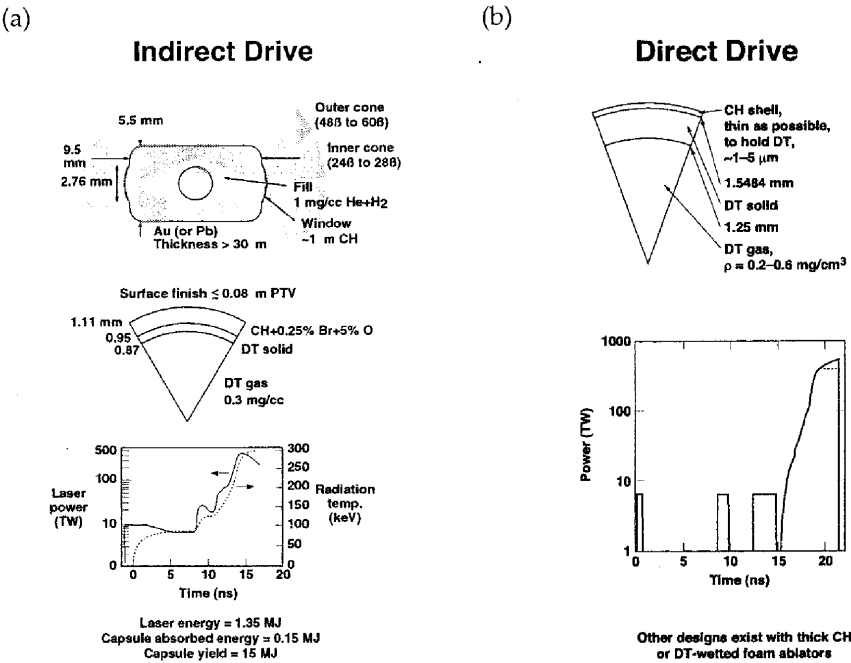


Figure 10. The NIF baseline indirect (a) and direct (b) target designs along with the laser pulse shapes used to drive them.

More recently, work exploring higher gain on indirect drive has shown promise. In Figure 11, the energy-power parameter space available on the NIF is shown along with the location of the nominal gain 10 design and one with gain 30. As shown in the figure, by optimizing the hohlraum and laser, it may be possible to produce indirect-drive targets where the capsule absorbs >600 kJ of x rays (the baseline NIF capsule absorbs 150 kJ of x rays). Such targets would produce gains greater than 50!⁶

- ◆ Lower power, longer pulse shapes can give more energy from NIF (260 eV vs 300 eV)
- ◆ Material mixtures ("cocktails") reduce hohlraum wall losses
- ◆ Slightly larger capsule/hohlraum size increases coupling efficiency to capsule
- ◆ Longer pulses increase the radiation fraction absorbed by a capsule
- ◆ Slight LEH closure reduces hole losses

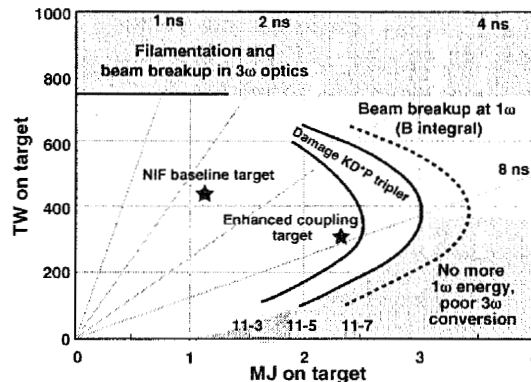


Figure 11. We are exploring ways to increase the capsule energy on the NIF for indirect-drive designs.

For IFE to be successfully developed, target gains of 30 to more than 100 are required. The exact target gain depends upon the driver efficiency in converting electrical energy into beam energy. For an economical power plant, the product of driver efficiency and target gain should be larger than about 10.^{3,4} For laser drivers, driver efficiencies of 7–15% may be attainable.⁷ Therefore, target gains of 70 to 140 are needed. For heavy-ion drivers, efficiencies of 25 to 35% may be possible,⁸ thus requiring gains of 30 to 40. The NIF is expected to obtain ignition and gains of 10 (although recent work suggests that higher gains are possible).

Targets igniting in the NIF must be related to the targets that can obtain the necessary gain for an economical power plant. The key to relating target ignition in the NIF to the requirements for high gain is to look in detail at target ignition and propagating burn. A single parameter like target gain is insufficient to understand this relationship. Figures 12a and 12b show the ignition and propagating burn processes to be demonstrated on the NIF. Figure 12a shows the configuration of a compressed, heated high-gain target at the time of ignition. At peak compression, the isobaric fuel is composed of a hot (10 keV) low-density hot spot and a dense ($\rho > 400$ g/cm³), low-temperature, near-Fermi-degenerate main fuel. If the hot-spot areal density (ρr) exceeds 0.3 g/cm² (an alpha range), the alpha particles will deposit their energy locally and boot-strap the temperature achieved through the PdV work of the compression. As the hot-spot temperature bootstraps upward, the reaction rate increases. Alpha particles produced near the edge of the hot spot will deposit their energy into the surrounding layer of cold compressed fuel to start a propagating thermonuclear burn front. This burn wave will propagate through the cold surrounding fuel, which must have a ρr of 2–3 g/cm². At this value, 1/4 to 1/3 of the fuel will be burned. The NIF must not only demonstrate ignition but must also demonstrate self-sustained propagating burn so

that if a greater mass of fuel is compressed, there will be confidence that the propagating burn front will consume the additional fuel.

Figure 12b shows the temperature-pr map of possible conditions in an ICF target. Ignition and propagating burn are only possible in a target when the gains due to PdV work and alpha particle deposition are greater than the losses due to heat conduction and radiation. In this map we have shown the dividing line between the regions where gains or losses dominate for an implosion velocity of 3×10^7 cm/s. This map shows the region achievable on Nova and that achievable on the NIF. NIF target implosions must move through this map staying in the gain region. This is sometimes referred to as moving through the "hole" in the Wheeler diagram (after John Wheeler of Princeton University who first suggested this as a criterion for inertial fusion ignition).

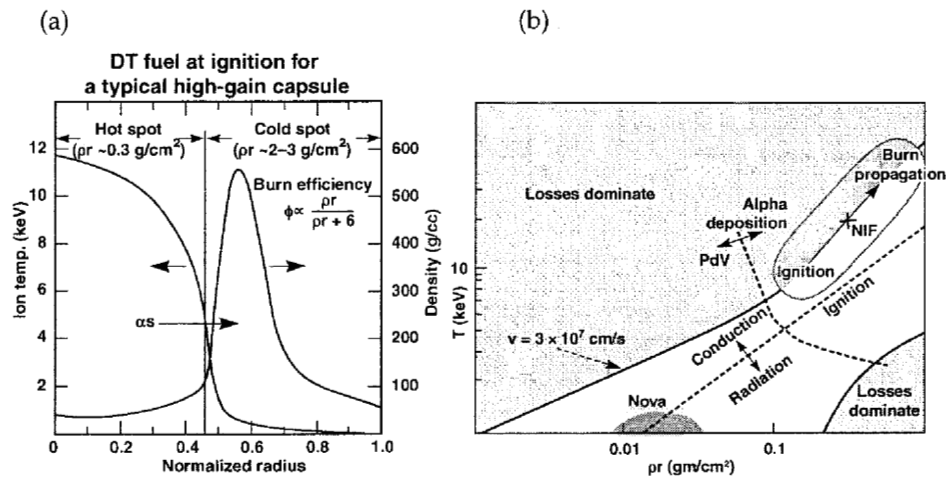


Figure 12. The increased energy of the NIF allows a large-enough fuel areal density for fusion ignition and propagating burn.

Nova experiments have achieved a pr of about 0.02 g/cm^2 , a temperature of about 1 keV , and a gain of 0.001 .⁹ With the NIF we expect a pr of $\sim 1 \text{ g/cm}^2$, temperatures of about 10 keV (with alpha particle deposition augmentation), and therefore a gain of order 10 .¹⁰

Detailed simulations of both NIF ignition targets and high-gain targets have been used to design the ignition target to be "hydrodynamically" equivalent to the high-gain target. By this we mean that, up to the point that the ignition target runs out of compressed cold fuel, the physics of ignition and propagating burn in the NIF ignition target mimics what would go on in a high-gain target. The propagation issues for high-gain capsules will be settled by ignition and propagating burn experiments in the NIF.

Figure 13a shows the details of the calculated temperature and density profiles for both ignition and high-gain targets (i.e., for capsule absorbed energies of 0.2 and 2 MJ , respectively). Figure 13b shows the ion temperature vs pr profile at various times during the burn of each capsule. The ignition target is shown as the set of solid lines while the high gain target is shown as the set of dashed lines. The ignition capsule quenches due to disassembly at a pr of $1\text{--}1.5 \text{ g/cm}^2$. However, up to that point, its profile is very similar to

that of the high-gain target. Therefore, we would expect that the demonstration of ignition and modest gain in the ignition target would be sufficient to have high confidence that high gain could be achieved with a driver large enough to compress an increased fuel mass. In addition to this type of analysis, DOE is also exploring the value of a single-pulse high-yield fusion explosion which would result from a higher mass implosion. This study may identify a need for a high-yield post-NIF facility for national security purposes.

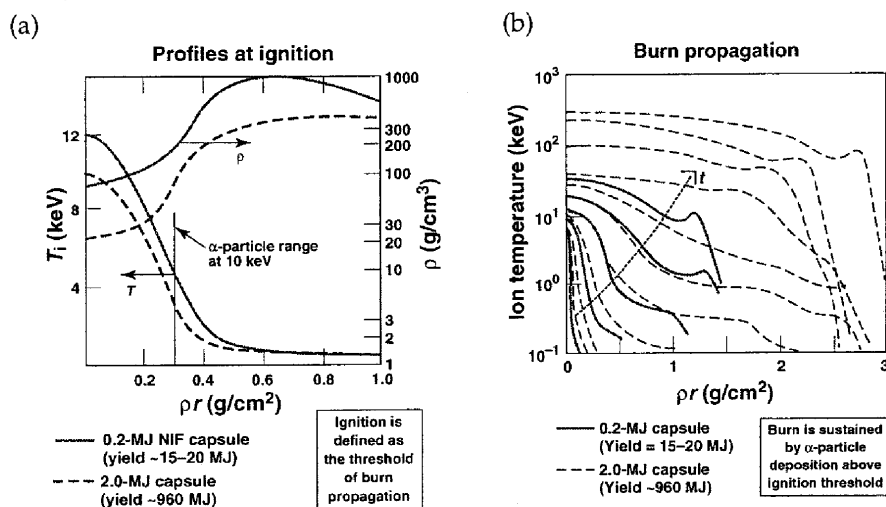


Figure 13. (a) Temperature and density profiles for both ignition (0.2-MJ capsule absorbed energy) and high-gain (2-MJ capsule absorbed energy) targets for a ρr of 1 g/cm². (b) Ion temperature vs ρr at a variety of times in capsule burn for the ignition and high-gain targets.¹¹

4. HIGH-ENERGY SCIENCE FROM ICF

For the past several years a modeling and experimental program has been under way to explore the utility of ICF science and facilities in the areas of astrophysics, planetary science, and shock and condensed-matter physics. Experiments are now under way in the areas of supernovae explosion hydrodynamics, radiative jets (Herbig-Haro objects), solid-state flow relevant to the interiors of terrestrial planets, photoablation, ablation front instabilities (the "pillars of creation" recorded by the Hubble telescope), and equation of state along the principal Hugoniot of hydrogen (relevant to the Jovian planets and Brown dwarfs) and other materials. This work has been very successful and several illustrative examples are shown in this section.

4.1 Supernova Explosion Hydrodynamics

Figure 14 shows the striking similarity of the hydrodynamic instabilities between an imploding ICF capsule and an exploding core collapse supernova. It can be shown that such physics are well described by Euler's equation

$$\frac{\delta \bar{V}}{\delta t} + (\bar{V} \cdot \nabla) \bar{V} = -\frac{\nabla P}{\rho}$$

and by making the following scale transformations

$$\begin{aligned}\rho &= A_1 \rho \\ P &= A_2 P \\ \bar{X} &= A_3 \bar{X} \\ \tau &= \left(\frac{A_1}{A_2} \right)^{1/2} A_3\end{aligned}$$

The physics are Eulerian invariant. Figure 15 shows that, by proper design of a laboratory experiment, the calculated velocity, density, and pressure profiles of a supernova explosion can also be reproduced. With this motivation, recent planar experiments have validated hydro instability codes utilized in supernova calculations.

Figure 16 shows the experimental arrangement, x-ray radiograph, and model/data comparisons of Richtmyer-Meshkov and Rayleigh-Taylor instability growth at the Cu-CH interface of an accelerated target employed in the laboratory experiments. Excellent agreement is observed. Recent striking experiments, shown in Figure 17, display the explosive phase of an x-ray heated cylinder, which qualitatively compares quite well to the calculated supernova explosion.

Simulations of possible experiments on the NIF have been done to explore the expanded capabilities the NIF will bring. Figure 18 shows the highly nonlinear turbulent mixing that is calculated to occur in such experiments and compares it with simulation of supernova 1987A. Based on these types of calculations and the experiments that have been conducted on Nova and elsewhere, the NIF should make a major contribution to our understanding of the nonlinear hydrodynamics of supernovae explosions.

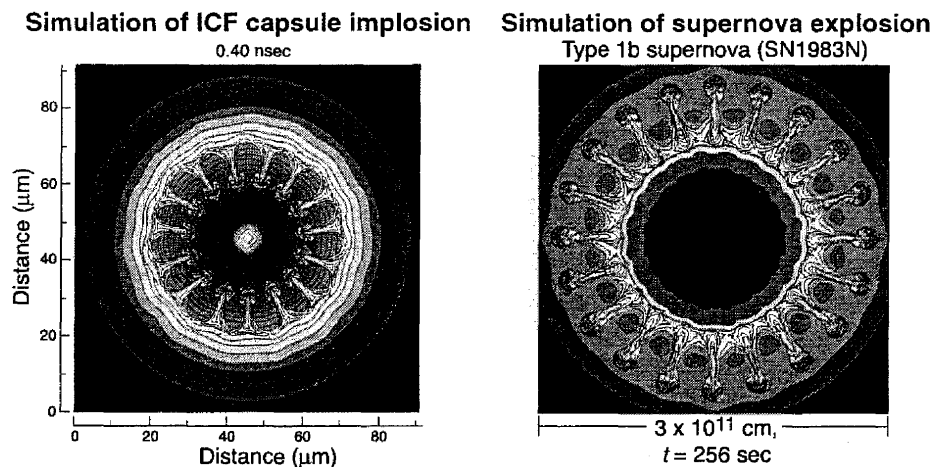


Figure 14. Striking similarities exist between hydrodynamic instabilities in ICF capsule implosions and core-collapse supernova explosions.^{12, 13}

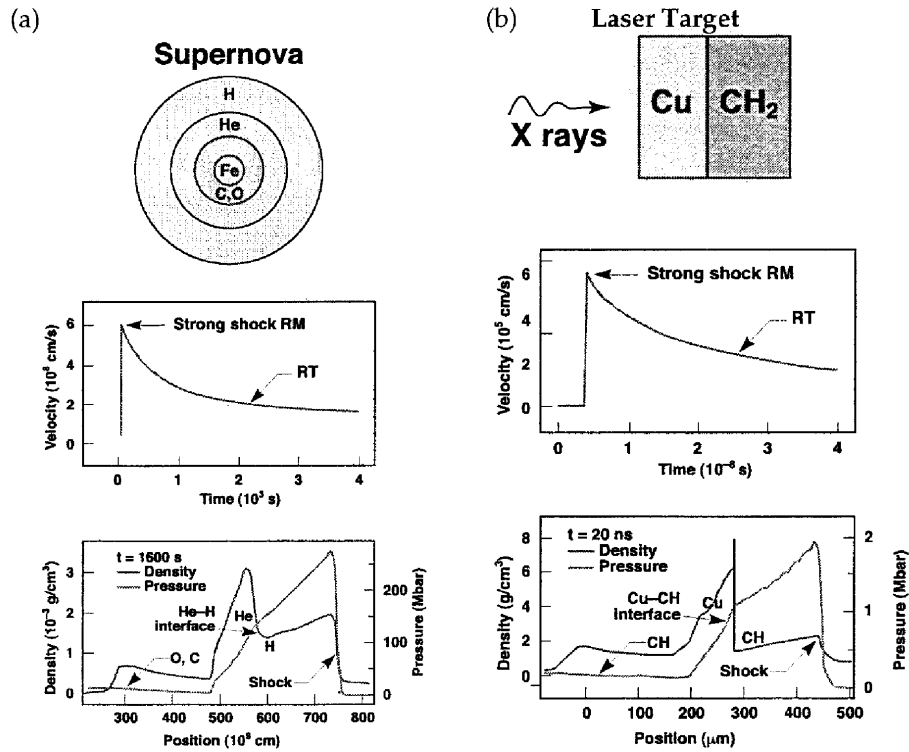


Figure 15. Velocity, density, and pressure profiles for a supernova (a) that are reproduced in a laboratory experiment driven by laser-generated x rays (b).¹⁴

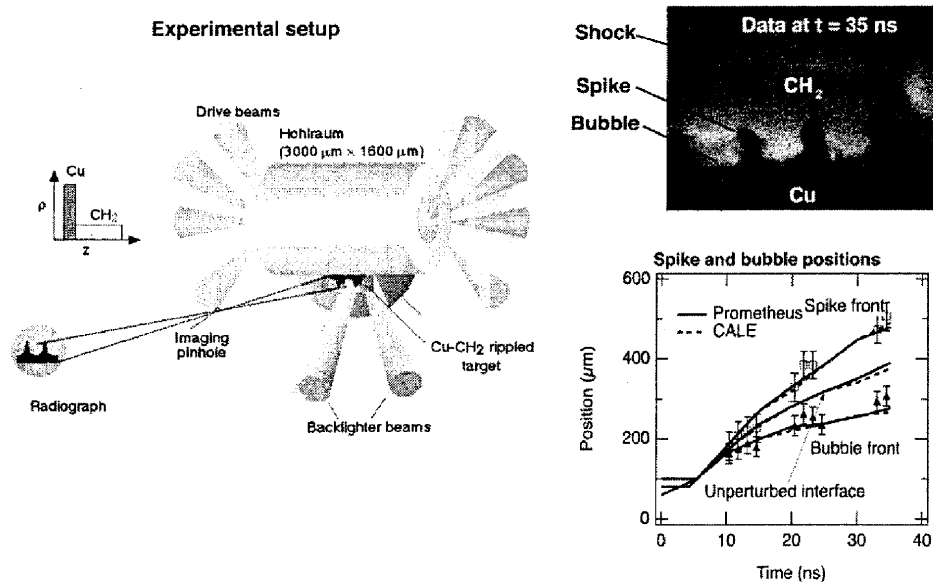


Figure 16. Scaled core-collapse supernova experiments on the Nova laser mimic the hydrodynamics at the helium-hydrogen interface with surrogate materials. Bubbles, spikes, mushroom caps are observed, and bubble and spike positions are simulated with supernova code PROMETHEUS, and with CALE.^{15, 16}

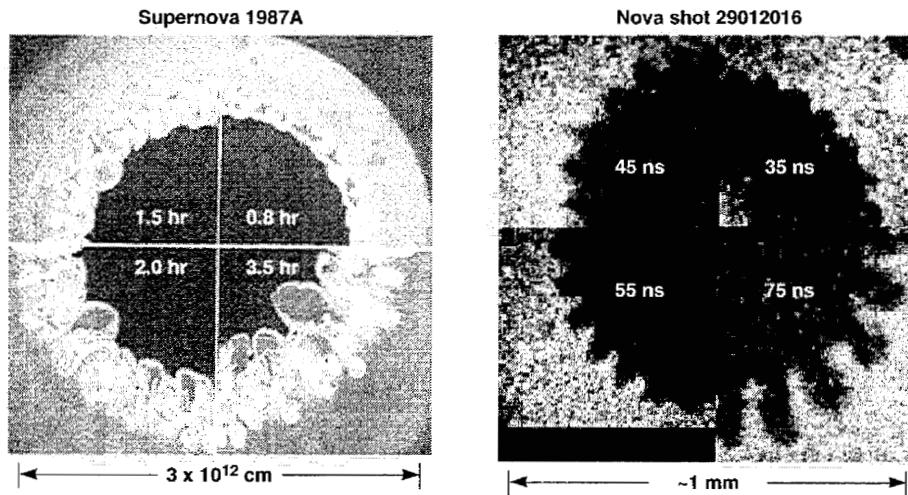


Figure 17. Hydrodynamic instabilities occur in supernovae; scaled reproductions are created in laser experiments.^{17, 18}

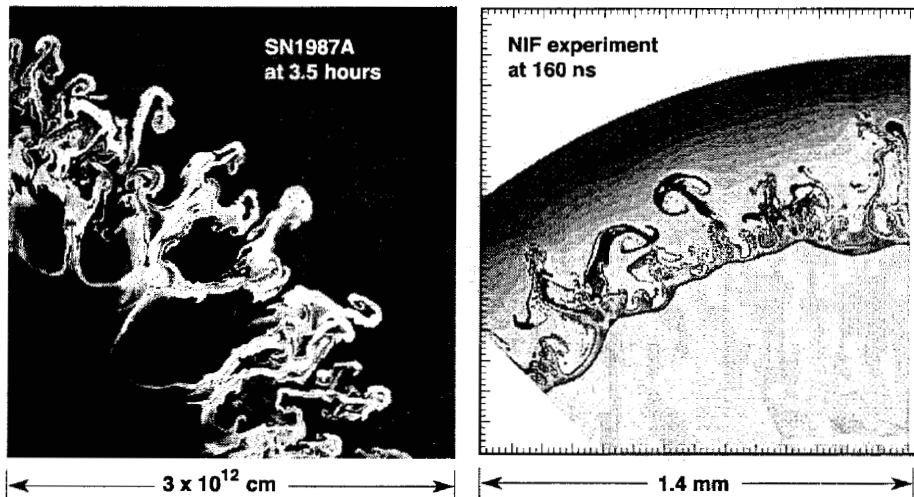


Figure 18. More star-like, scaled supernova experiments are being designed for the NIF. These will be in spherically divergent geometry with multiple layers and multimode perturbations.^{19, 20}

4.2 Radiative Jets

Recent experiments have now begun to explore astrophysical phenomena where Euler's equation is no longer valid, i.e., when radiative transport is not negligible. Herbig-Haro or radiative jets are examples of such phenomena (Figure 19). Calculations indicate that such high Mach number jets undergo radial collapse to reestablish pressure equilibrium following radiative loss. Adiabatic jets, in contrast, remain extended in radius. Experiments at Nova and the Gekko laser at Osaka University have produced and diagnosed radiative jets using

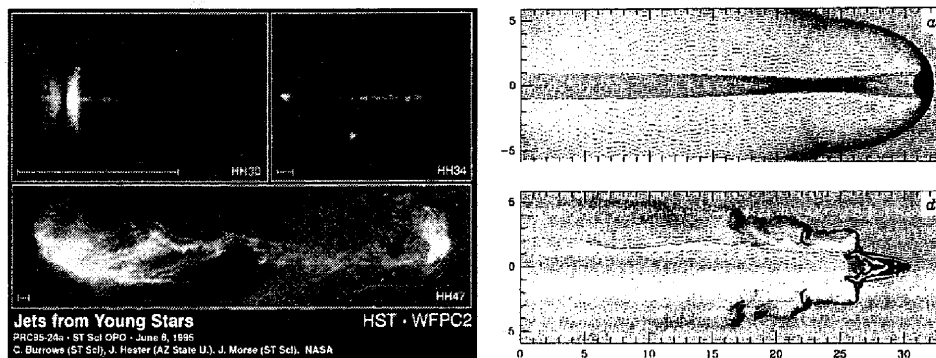


Figure 19. High Mach number jets occur in astrophysics and can be created in the laboratory using intense lasers.^{21,22} In an adiabatic jet (no radiative cooling), heat is trapped inside, and jet “puffs up” (top right). In an radiative jet (photons remove heat), jet collapses to reestablish pressure equilibrium (bottom right).

innovative conical targets. Figure 20 shows calculated x-ray emission and absorption profiles of such a laboratory jet and comparison with experiments. This is excellent agreement especially for the jet's electron temperature of 250 eV (an adiabatic jet would have a temperature of 500 eV).

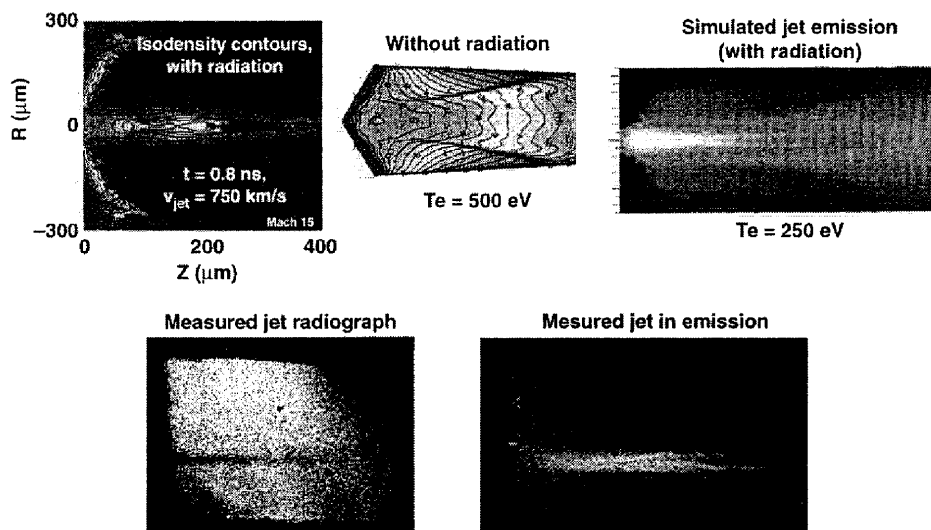


Figure 20. Simulations, experiment in remarkable qualitative agreement.²³

4.3 Equation of State

An understanding of the equation of state (EOS) of hydrogen at pressures exceeding 1 Mbar is important for planetary science, brown dwarfs, and ICF. Study of the EOS along a principal Hugoniot for numerous materials up to tens of megabars has been made possible by ICF facilities. For example, a recent study of the compression of liquid deuterium at pressures from 0.2 Mbar to 3.4 Mbar using Nova has revealed high compressibility. This is now understood as linked to pressure-induced molecular disassociation corresponding to the transfer to “metallic like” hydrogen. The results, shown in Figure 21, were obtained with numerous diagnostics. Similar insulator to metal transients have also been seen for LiF at ~6 Mbar and carbon (diamond) at ~10 Mbar.

Further experiments will study off-Hugoniot states of higher density and lower temperature using diamond anvils and temporally shaped laser pulses. If conditions of 100 g/cc and temperatures <1 eV can be reproduced, then pyconuclear fusion may result. Pyconuclear fusion occurs when the proximity of nuclei in cold compressed D-T tunnels through the Coulomb barrier producing significant fusion rates. The ability to conduct off-Hugoniot EOS measurements in materials such as H, He, H₂O, N₃, Si, and C at pressures exceeding tens of megabars with the NIF will be of significant interest to a broad community.

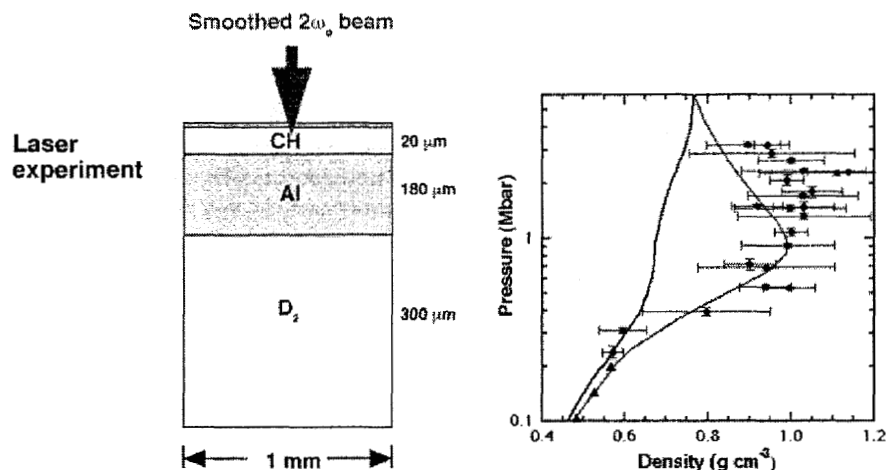


Figure 21. Laboratory experiments used Nova laser energy to produce a shock that allowed measurement of the equation of state of hydrogen at megabar pressures. This discriminated between competing models.²⁴

5. ULTRA HIGH ENERGY DENSITY PHYSICS WITH PETAWATT LASERS

The development of chirped pulse amplification has made possible extremely high-power ($>10^{15}$ W), short-pulse (<10 – 12 fs), high-brightness lasers which can irradiate targets at intensities approaching 10^{21} W/cm².²⁵ Such lasers open up new opportunities in relativistic plasma physics. Experiments have shown that a significant fraction of high-intensity light is converted into relativistic electrons^{26,27} with energies up to 100 MeV^{27,28} as shown in Figure 22. Intense gamma rays created in electron collisions have led to the production of positrons,²⁸ also shown in Figure 22. As shown in Figure 23, these gamma rays induce (γ, n) and (γ, p) nuclear reactions,

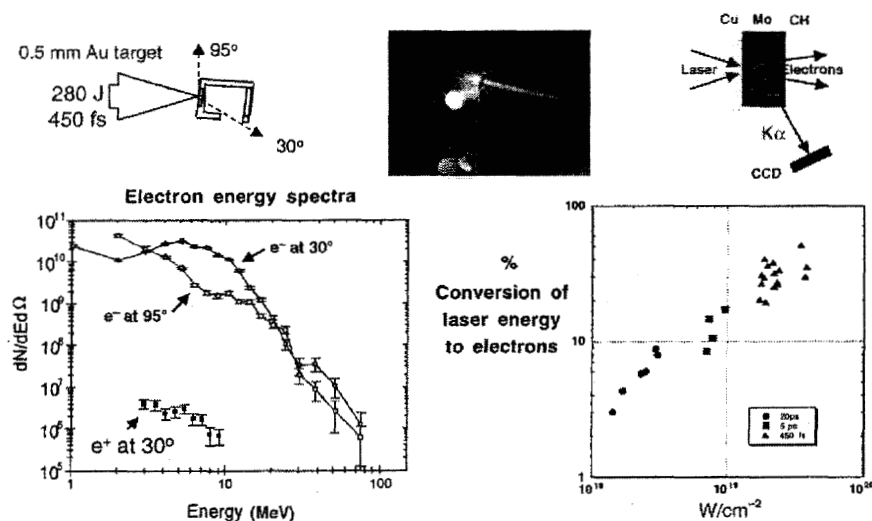


Figure 22. Petawatt experiments at $>10^{20}$ W/cm² have produced relativistic electrons and initial evidence of electron-positron plasmas.

photo-dissociation of nuclei, and activated radionuclides in a wide range of materials.^{28,29} High-energy proton beams are generated and, in turn, induce strong (p,n) nuclear reactions. These data suggest that high-intensity lasers may provide new sources of ions, nuclear particles, and radionuclides which may have significant future scientific and technical applications.

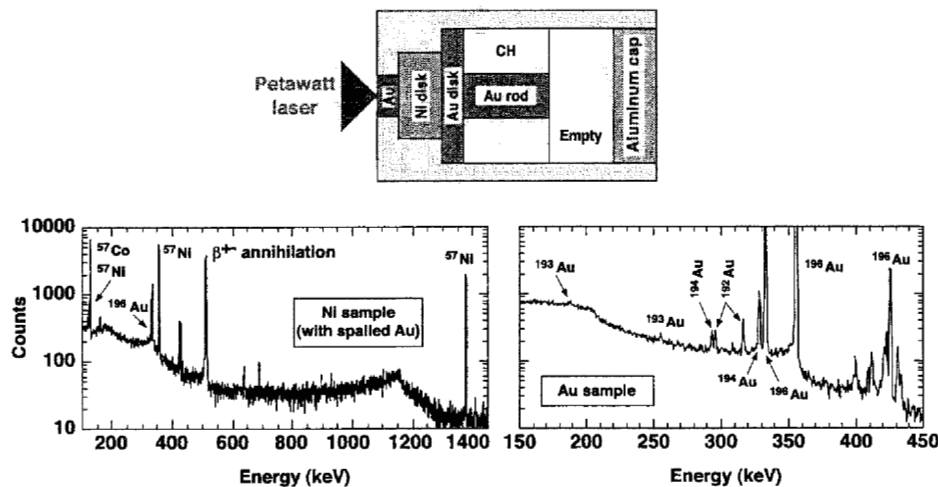


Figure 23. The Petawatt laser at LLNL has produced strong nuclear (γ ,xn) activation at thresholds exceeding 50 MeV.

6. IRE AND IFE CONCEPTS

The recommended system requirements for an IFE laser driver are as follows: efficiency $> 5\%$, reliability $> 10^9$ shots, and cost $< \$1.5B$. The recommended target requirements are as follows: wavelength $< 0.4 \mu\text{m}$, beam smoothness $< 0.1\text{--}1\%$ on target, and pulse shape control $< 0.2\%$. Based on these requirements, there are three drivers with a reasonable chance of application to fusion energy: a KrF laser, a diode-pumped solid-state laser (DPSSL), and a heavy-ion accelerator. The advantages of a KrF laser are its lower cost and good beam uniformity, but its efficiency ($< 6\text{--}7\%$) and durability need development. The advantages of a DPSSL are its high efficiency ($10\text{--}20\%$) and excellent durability ($> 10^9$ shots), but the price of laser diodes makes a DPSSL cost more, and its beam uniformity needs development if the laser is used with direct-drive targets. The advantages of a heavy-ion accelerator are its high efficiency ($> 25\%$) and excellent durability, but its cost and final-focus parameters need development.

The Nike KrF facility, with 60-cm beam apertures, uses angular multiplexing to obtain power multiplication on target. A 4-ns front-end pulse is divided (encoded) into multiple beams with beam splitters, sent through a 200–300 ns long-pulse amplifier, and recombined (decoded) to overlap on target. The “30-cm Rep-Rate Laser” is an integrated KrF laser

facility that could be used to develop most of the needed IFE technologies with 400 J in a $30 \times 30 \text{ cm}^2$ aperture using a 500 kV, 111 kA, 100 ns electron beam with a $100 \times 30 \text{ cm}$ cathode. The “hibachi” foil-like separator between the electron accelerator and the KrF laser gas cell would be one area of concentrated research to increase efficiency, repeatability, and durability.

Overall, the rep-rated KrF program has five elements. First, there is the 5 Hz >400 J Electra laser with rep-rate laser technology applied to a uniform beam. Second, a rep-rated 10 J preamp and pulse shaping system constitutes an advanced front end of suitable size for an IFE reactor, where pulse shapes, focal profiles, and zooming are being investigated for IFE. Third, KrF physics is being improved with code development and validation with experiments on the Nike laser to investigate intrinsic efficiency, and electron beam transport and deposition close to IFE conditions and scale. Fourth, an advanced coating/optics program is investigating amplifier window coatings, high-damage-threshold optics, and final optics. Fifth, KrF system studies are underway to investigate conceptual designs for IFE reactor beam lines complete with laser architectures and reactor/target interface issues.

A diode-pumped solid-state laser (DPSSL) has much in common with NIF technology—both are storage lasers operating at $1 \mu\text{m}$ wavelength with conversion to the third harmonic, and both share many of the same architectural and technological features (deformable mirror, multipass switch, front-end laser, segmented amplifier with cooling fluids, beam conditioning upon final focus, etc. The target performance on the NIF therefore directly translates to DPSSL drivers. However, several enhancements must be made to the NIF architecture to make DPSSLs suitable for IFE. The flashlamps must be replaced by laser diodes to provide high pumping efficiency, long lifetime, and less thermal loading. The Nd:glass laser medium must be replaced by Yb:crystals to offer the four times longer energy storage time required for high efficiency with diode pumping, and to offer several times higher heat conductivity to facilitate gas cooling for high rep rates. The passive Nd:glass cooling must be replaced by forced gas cooling to manage the heat dissipated in the gain medium, which for Yb:crystals reduces thermal distortions to a simple beam steering. Finally, the debris shield must be replaced by a heated ($\sim 400 \text{ C}$) fused silica optic to continuously anneal the discoloration caused by neutron target irradiation. The Mercury laser (Fig. 4) includes most of these replacements.

Phase I for the DPSSL program has well-defined deliverables: efficiency >10% with 3ω conversion, diode price $\sim 50\text{¢/W}$ for an IRE with a credible path to 7¢/W for IFE, beam smoothness <1% integrated over 0.2–1 ns for low L-modes on target, 15-cm-aperture (Yb:S-FAP) gain media with high optical quality, frequency conversion of $\sim 80\%$ efficiency at average power with the required bandwidth for smoothing, technology integration for reliable operation at 10 Hz, and scalability to attain the kJ or MJ level. Figure 24 lists some of the critical issues that a DPSSL-driven IRE can address.

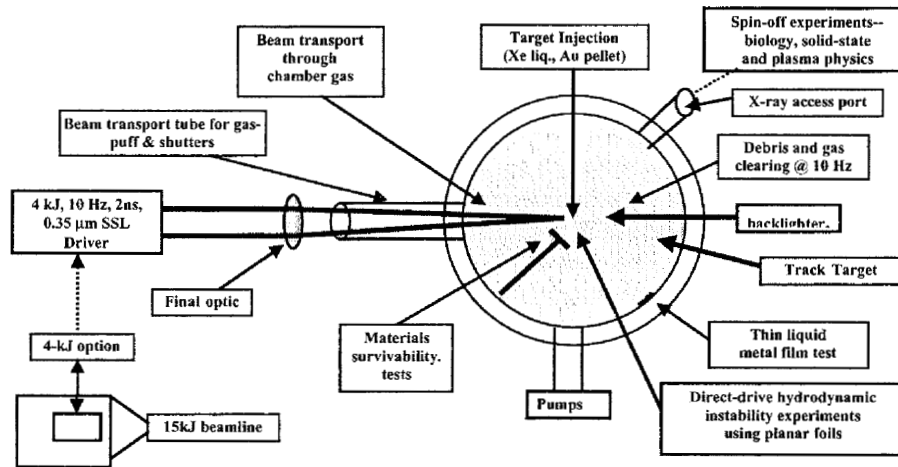


Figure 24. An Integrated Research Experiment (IFE) concept based on a DPSSL, showing how one 4-kJ laser module integrated with a fusion chamber can investigate many IFE-related issues.

Accelerators are also thought to be well matched to the engineering requirements of fusion power production. The scale, complexity, cost, average power consumption, ion kinetic energy, focal spot size, and standoff of existing accelerators are roughly comparable to, or exceed, IFE power production requirements (e.g., with several MJ of beam energy in existing accelerators). Moreover, energy can be added to beams in small increments for low component stress levels. Focusing lenses are electric and magnetic fields, so coils and insulators can be shielded from x rays and neutrons. Beams are transported in vacuum, and 10^{12} W dc can be stored for days in a typical storage ring. Thus, accelerators possess reliability, long lifetime, and high pulse repetition rates. An accelerator is also 25 to 35% efficient because it is merely a series of electrical transformers.

An induction accelerator is one example which requires a variety of beam manipulations to achieve an IFE target irradiation. Power amplification to the required 10^{14} to 10^{15} W level is achieved by beam combining, acceleration, and longitudinal bunching. The ion source and injector can produce a beam that can be accelerated with electric focusing, followed with acceleration with magnetic focusing, compression, and bending with focusing into a chamber to achieve 10 GeV with ~4kA per beam. Beam quality and cost are the important issues, as well as transport of the beam into the chamber and to a target. ILSE and HTE were scaled versions of this type of machine.

An IRE based on an accelerator driver would need to validate long-term transverse and longitudinal beam dynamics at current levels >100 A, while enabling definitive focusing experiments on a variety of focusing modes >100 MeV. The IRE would also validate beam-target interaction physics at the multi-kJ

level and $>3 \times 10^{12}$ W/cm². Desirable IRE goals would include exploration of target concepts unique to ions at $>10^{13}$ W/cm², and possible reconfiguration to serve as the front end of a full-scale driver. The program must demonstrate reliability and long life (10^9 to 10^{10} pulses), high efficiency ($>15\%$), and predictable as well as acceptable cost of electricity (COE <5 ¢/kWh).

Researchers have developed one chamber concept for each of direct and indirect drive, and both are comparable in size, cost, complexity, and COE to the Westinghouse APWR 1300 Advanced PWR Fission Reactor. The HYLIFE-II concept with ion indirect drive uses a liquid (Flibe) first wall to achieve a 30-year life. The Sombrero concept with either KrF laser or DPSSL direct drive uses a C/C-composite dry first wall with Li₂O granules.

For fusion chamber technology, the Phase I deliverables address "gateway" issues, as shown in the following table.

Table 2 Phase I chamber technology deliverables for laser and heavy-ion drivers.

Issue	Laser-driver deliverable	Heavy-ion-driver deliverable
Final optics survivability	<ul style="list-style-type: none"> • Use spallation sources to extend hot-fused silica neutron irradiation data • Test grazing incidence metal mirrors • Measure shock effects from anticipated fireballs 	<ul style="list-style-type: none"> • Demonstrate clearing with properly scaled model of a liquid experiment that includes simulated target blast forces
First wall chamber lifetime	<ul style="list-style-type: none"> • Reassess carbon first-wall lifetimes • Assess effectiveness of x-ray protection with gas • Measure erosion rates from granular solid coolants • Design rapid first-wall change-out procedures 	<ul style="list-style-type: none"> • Design self-consistent magnet/chamber that simultaneously accommodates the size of the final focus magnets, shielding, and necessary placement to hit a ~3 mm radius spot
Environment and safety	<ul style="list-style-type: none"> • Measure T2 inventories in high-T carbon composites • Validate dust transport models • Design to minimize long-lived radionuclides 	<ul style="list-style-type: none"> • Design to minimize radioactive waste and release of long-lived nuclides
Other important deliverables	<ul style="list-style-type: none"> • Determine how much the chamber T and P must be lowered for cryogenic targets to survive intra-chamber conditions upon injection • Demonstrate beam focusability in a 1 Torr Xe gas environment 	<ul style="list-style-type: none"> • Demonstrate required beam quality after transport through chamber gas • Demonstrate survivability of cryogenic targets upon injection • Measure the focusability of ion beams to ~3 mm radius in a realistic chamber environment

7. INNOVATIVE SPECULATIVE CONCEPTS FOR IGNITION

Technology advances have made possible an innovative ignition concept called "fast ignition," based on ultra-high brightness lasers. The fast ignitor employs less sophisticated capsule compression followed by a ~200-ps 10^{18} W/cm² laser pulse to "channel" through to the fuel core, and then a ~30-ps 10^{20} W/cm² laser pulse to ignite the fuel through the channel.^{30,31} The implosion requirements

are therefore less stringent for mix, convergence, and other parameters, while affording significantly more target gain. However, significant R&D is required to explore the potential for this concept. The Petawatt laser at LLNL will be performing fast-ignitor physics experiments in a dedicated chamber until the end of 1999. Future experiments may be conducted at Gekko XII, Omega, and other facilities.

8. CONCLUSIONS

Inertial confinement fusion is poised to take its place in the community of fusion energy approaches. Significant challenges remain but the attractive energy features, affordable development plan, and construction of the NIF provide a significant opportunity for development in the next decade. Finally, the richness of the science of ICF will help broaden the constituency for fusion and contribute to diverse fields as astrophysics, and shock and condensed-matter physics.

The prospects for developing IFE as a power source which is "real, clean, and cheap" are improving. The NIF will produce ignition and provide driver requirements to achieve high gain. NIF technology is demonstrated, and the project is scheduled for completion and initial operation in the 2003 to 2007 time frame. KrF and DPSSLs are promising drivers for direct-drive IFE, and DPSSLs and heavy ions look promising for indirect-drive IFE. A moderate-scale (\$45 M/year) driver and chamber development plan for IFE is proposed that leads to an IRE to test driver and chamber concepts. In addition, the inertial fusion program has provided valuable spin-offs to industry and science. We are therefore planning to achieve an IFE demonstration power plant by about 2035.

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